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ABSTRACT

A new geophysical data set off La Réunion Island (western Indian Ocean) reveals a large volcaniclastic submarine fan developing in an open-ocean setting. The fan is connected to a torrential river that floods during tropical cyclones. Sediment storage at the coast is limited, suggesting that the sediments are carried directly to the basin. The fan morphology and turbidites in cores lead us to classify it as a sand-rich system mainly fed by hyperpycnal flows. In the ancient geological record, there are many examples of thick volcaniclastic successions, but studies of modern analogues have emphasized mechanisms such as debris avalanches or direct pyroclastic flow into the sea. Because the Cilaos deep-sea fan is isolated from any continental source, it provides information on architecture and noncatastrophic processes in a volcaniclastic deep-sea fan.

INTRODUCTION

La Reunion Island is an active basaltic shield volcano, 220 km in diameter, rising ~7000 m from the Indian Ocean floor. The island is constructed on Paleocene oceanic crust and is considered to be the surface expression of a hotspot (Duncan, 1990). The submarine flanks of La Réunion are mainly debris avalanche deposits (Oehler et al., 2008). Little previous attention has been paid to the volcaniclastic sedimentation on the slope apron and the adjacent abyssal plain.

Studies on volcaniclastic sedimentation during the 1980s and 1990s were focused on short-term, high-amplitude events, such as debris avalanches and pyroclastic flows (Fisher, 1984; Moore et al., 1989; Schmincke and Sumita, 1998; Masson et al., 2002). Very high-resolution studies carried on the submarine flanks of La Palma and El Hierro in the Canary Archipelago (Wynn et al., 2000), as well as on Stromboli volcano in the Mediterranean Sea (Kidd et al., 1998; Casalbore et al., 2010), have shown evidence of sedimentary processes that are not linked with giant volcanic landslides. Recent advances on source-to-sink processes in volcanic setting (Manville et al., 2009) offer a more dynamic focus on volcaniclastic sedimentation by putting together the nature and dynamics of the volcanic products and the environmental setting.

To the authors' knowledge, no previous studies have examined the case of a torrential river supplying a Quaternary volcaniclastic turbidite system. We present here the case of the Cilaos deep-sea fan, the sediment source of which is a torrential river draining a dormant volcanic center on La Réunion. Our objective is to show that long-term erosion processes and high sediment supply in a volcanic-island setting can also form deep-sea fans similar to siliciclastic ones.

We combined acoustic backscatter images and swath bathymetry data (Simrad EM12D and EM120), 3.5 kHz echosounder profiles, and piston cores collected during cruises FOREVER (N/O *L'Atalante*) and ERODER 1 (N/O *Beautemps-Beaupré*) in 2006. Laser-diffraction grain-size analysis and X-ray imaging were performed on the cores. Due to the low content of bioclasts in our core sampling, radiocarbon dates were not conclusive.

SOURCE OF THE VOLCANICLASTIC TURBIDITE SYSTEM

The Cilaos deep-sea fan is connected to a small drainage basin (360 km^2) up to 3000 m elevation via the Rivière Saint-Etienne (Figs. 1 and 2). The river has built an alluvial fan-delta no older than 350 ka, with a volume of ~25 km^3 (Saint-Ange, 2009). The river bed is composed of poorly sorted, coarse-grained sediments, ranging from sands to boulders (Fig. 3). The present river outlet is directly connected to a submarine valley. There is no shelf in front of

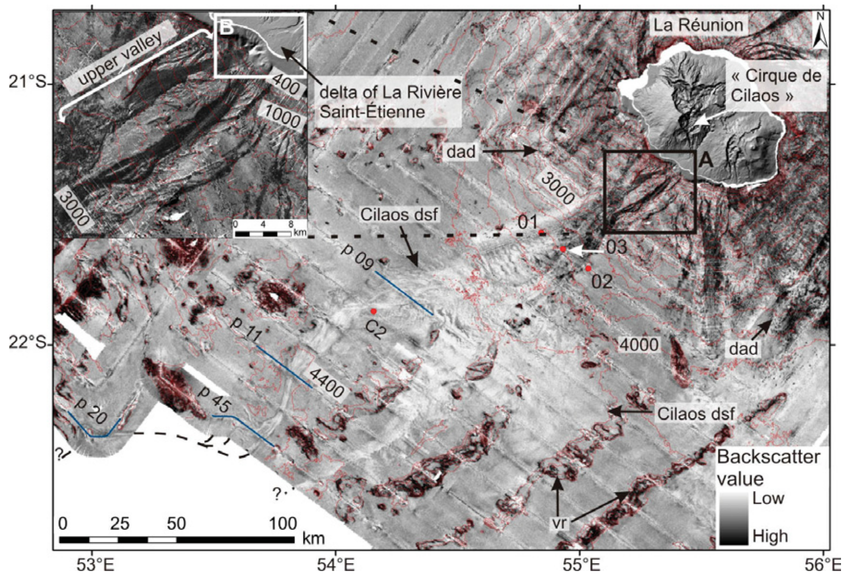

Figure 1. Acoustic backscatter images of southwestern part of La Réunion gathered during recent cruises FOREVER and ERODER. Red dots indicate location of cores, and blue lines indicate location of 3.5 kHz echosounder profiles shown in Figure 5. A: Close-up of La Rivière Saint-Etienne valleys. B: Location of Figure 2. Abbreviations: dad—debris avalanche deposits; dsf—deep-sea fan; vr—volcanic ridges.

†Deceased 21 August 2008.

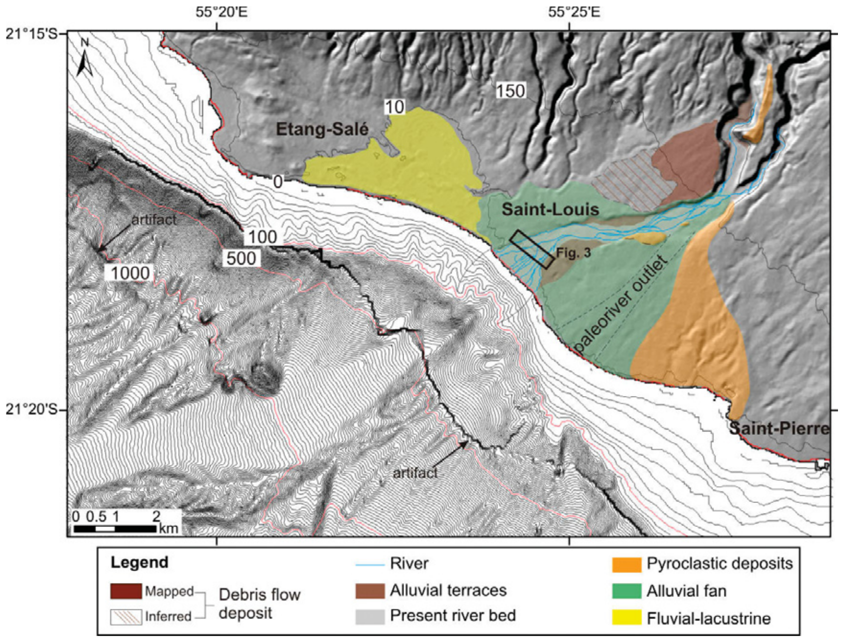

Figure 2. Map of alluvial fan of Rivière Saint-Etienne and bathymetry of upper part of slopes (contour interval: 10 m; artifact in drawing of contour lines highlights limit between swath and conventional bathymetry data sets). Onshore shaded topography was produced using a digital terrain model provided by Institut Géographique National (IGN), France. Conventional bathymetry data were provided by Service Hydrographique et Océanographique de la Marine (SHOM), France.

Figure 3. Photo of Rivière Saint-Etienne after Hurricane Gamède (2007). Note size of boulders (cars for scale).

the alluvial fan (Figs. 1 and 2; Fig. DR1 in the GSA Data Repository[1]), implying almost no sediment storage capacity at the coast.

The sediments are transported by annual flash floods linked to the passage of tropical hurricanes and storms that increase the river discharge from 4.6 $m^3 s^{-1}$ up to 1500 $m^3 s^{-1}$, with flood velocity often higher than 6 m s^{-1} (SOGREAH, 1998). The river discharge doubles for a 10 yr return period, and centennial floods are estimated to reach 5000 $m^3 s^{-1}$ (SOGREAH, 1998). This type of flow leads to a mean solid load to the ocean of ~0.5×10^{-3} km^3 in a few days, and for a centennial flood the solid load is estimated around $1–2 \times 10^{-3}$ km^3 (SOGREAH, 1998). Severity of flooding is illustrated by the 2007 floods induced by Hurricane Gamède, during which the flow reached 2000 $m^3 s^{-1}$ (CGPC, 2007) and destroyed a major highway bridge (Fig. 3).

MORPHOLOGY AND NATURE OF THE CILAOS TURBIDITE SYSTEM

Feeder Valleys

The Cilaos turbidite system is more than 280 km long and 100 km wide (Fig. 1). It starts at the coast with a set of 2–4-km-wide valleys (mean bank elevation ~150 m), which merge into a single wider valley at about –3000 m of water depth (Figs. 1 and 4). These valleys are 70 km long and cut into debris avalanche deposits older than 500 ka (Oehler et al., 2008). Close to the coast, the valley floor gradient is ~8°, but it decreases quickly to reach 1° at the base of the volcanic edifice (Fig. 4; Fig. DR1). The high backscatter signal from valley floors is associated with very coarse sands and gravels, as revealed by piston core 03 (see Fig. 1 for location).

Morphology of the Fan

The upper part of the fan is characterized by fields of sediment waves (≥10 m high and 1 km of wavelength), the crest orientations of which are perpendicular to the valley axis. The sediment waves developed on slopes ranging between 2° and 0.4° (Fig. 4). They first start to grow on the western part of the lower valley (Figs. 1 and 4), where the height of the flank of the valley decreases significantly.

The main deep-sea fan is developed at ~4000–4500 m below sea level (mbsl) on a complex abyssal plain morphology shaped by northeast-southwest–trending volcanic ridges (Fig. 1). The volcanic ridges divide the turbidite system into three parts (western, central, and eastern), presenting contrasting backscatter acoustic facies.

The eastern and central parts of the fan show few distinct architectural elements, mostly short channels observed in their upper areas only. In contrast, elements such as sediment waves and channels are well developed in the western part of the fan. Here, the upper fan shows a braided channel system (Fig. 1; Fig. DR2), which ends quickly or merges into a single channel that extends down to the lower part of the turbidite system (Figs. 1 and 5). The 3.5 kHz data reveal

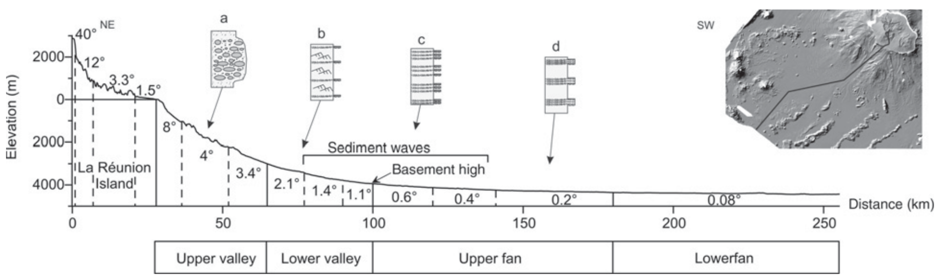

Figure 4. Topographic profile along Cilaos turbidite system (vertical exaggeration: 7×) and main sedimentary sequences observed along the system: a—gravel beds; b—ripple marks and laminated sands; c—laminated sands; d—sandy beds.

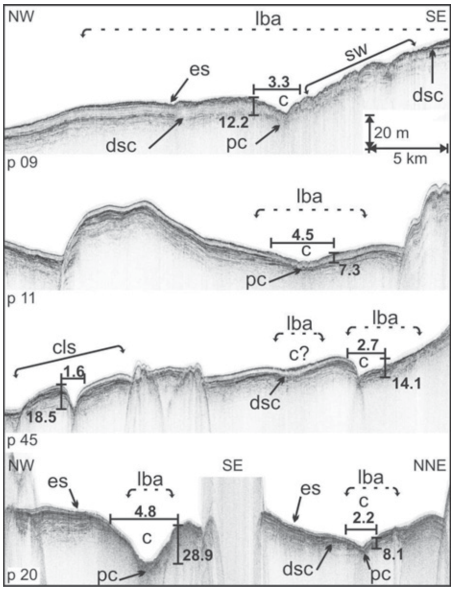

Figure 5. Part of four 3.5 kHz echosounder profi les spanning Cilaos fan (see location on Fig. 1). Numbers indicate width (km) and height (m) of channels. Abbreviations: c—channel; cls—channel-levee system; dsc—discontinuous subsurface refl ectors; es—erosion structures; pc—paleochannel; sw—sediment waves; lba—low-backscatter area.

that the channel morphology becomes deeper and more confi ned downstream (Fig. 5). In the distal part of the turbidite system, the channel reaches its maximum size, where it is ~5 km wide and ~30 m deep (Fig. 5, profile 20).

Nature of Sediments

The cores taken on overbank areas consist mainly of volcaniclastic detritus ranging from sands to clays, with silts and sands representing between 78% and 88% of the sediment. Sandy layers consist of dark basaltic fragments, brown glass, olivine, feldspar, pyroxene, and in some cases zeolites. True pelagic layers are rare, and hemipelagic layers are poor in bioclasts. Pumices are rare, but some are observed inside hemipelagic layers. The cores show classical turbidite sequences with traction deposits, such as ripple marks, laminated sand in places alternating with laminated bioclasts, and thick sand deposits, respectively, Tc, Tb, and Ta of the Bouma sequence (Fig. 4; Fig. DR3). These turbidites are rhythmic, with closely spaced sequences at the head of the fan and more interbedded hemipelagic sediment down the fan (Fig. 4; Fig. DR3).

SEDIMENTARY PROCESSES INVOLVED IN THE GROWTH OF THE TURBIDITE SYSTEM

Sediment Supply

The Cilaos deep-sea fan covers an area of ~15,000 km^2 and has a maximum thickness of 120 m (Saint-Ange, 2009). By comparison, it is as big as the siliciclastic fan of the Var (16,000 km^2) in the Mediterranean Sea, although its drainage basin is seven times smaller. The size of the fan in relation to its drainage system raises the question of rate of sediment supply.

Most hotspot-related volcanic islands in tropical or subtropical areas present three main similarities: (1) large production of volcaniclastic detritus linked to recurrent giant landslides (Moore et al., 1989; Masson et al., 2002; Oehler et al., 2008), (2) high magmatic production rates that frequently bring new material to erosion (Duncan, 1990; Schmincke and Sumita, 1998), and (3) among the highest worldwide erosion rates (Louvat and Allègre, 1997). The maximum denudation rates of some volcanic islands (Gran Canaria: 1.8 m k.y.$^{-1}$ [Menéndez et al., 2008]; Kauai: 4 m k.y.$^{-1}$ [Gayer et al., 2008]; La Réunion: 3.4 m k.y.$^{-1}$ [Louvat and Allègre, 1997]) are close to those estimated for active orogens (Taiwan: 3–6 m k.y.$^{-1}$ [Dadson et al., 2003; Himalaya: 2–5 m k.y.$^{-1}$ Burbank et al., 2003]). In the case of La Réunion, we propose that the continuous magmatic activity, which lasted at least 2 m.y. between 2.1 and 0.012 Ma in the Cilaos area (McDougall, 1971; Deniel et al., 1992), combined with the high erosion rate were able to continuously provide enough material, thus explaining the high sediment supply with respect to the small size of the drainage basin.

This explanation highlights the fact that long-term erosion processes account for a significant part of the volcaniclastic sediment output, and in the case of La Réunion, for the most significant part of the late Quaternary.

Sediment Transfer to the Basin

The drainage basin and the alluvial fan combined represent an area of 445 km^2. This value implies that the sediment storage capacity onshore represents only ~3% of the entire system. In view of the low storage capacity (Figs. 1 and 2), the high erosion rate, and the river discharge, the sediments cannot stay a long time onshore and are most likely transferred to the basin during flood events related to storm rainfall. Because the river is permanently connected with the submarine valley, there is no problem of accommodation due to the sea-level drops or rises, as they do not significantly impact the sediment transfer to the deep sea. All these parameters, together with the island's steep submarine upper slopes (Fig. 4) and the well-developed valleys cut into the debris avalanche deposits, provide an efficient transfer mechanism for volcaniclastic sediments from subaerial regions to the abyssal plain. The recurrent rhythmic sequences observed in cores and the obvious channel systems indicate that turbidity currents arrive frequently in the upper part of the fan. The resulting sediment deposits do not show the characteristic signatures of turbidites related to giant volcanic landslides as identified for other volcanic islands such as Canary Islands and Hawaiian Islands. In those areas, sediment record shows stacked subunits within a single thick turbidite bed (>1 m), indicating multiple stages of failure (Garcia and Hull, 1994; Wynn and Masson, 2003). This difference implies another mechanism for sediment transport than the catastrophic giant slopes failures.

In the case of La Réunion, the magnitude of river floods suggests that hyperpycnal flows contributed significantly to the development and the feeding of the Cilaos turbidite system. This hypothesis is also supported by the braided plain observed in the upper western part of the fan, the growth and development of which required a sustained flow, with high discharge and predominance of bed-load material (Hesse et al., 2001). The hypothesis of hyperpycnal flow feeding a turbidite basin has also been proposed in Iceland, where turbidites related to Jökulhlaup events are considered to have been a significant source of sediment to the Iceland Basin over the past 3 m.y. (Elliott and Parson, 2008). In addition, considering the high bed-load river type of La Rivière Saint-Etienne, small failures can occur immediately seaward of the main river mouth and secondary channels, as described for Squamish delta in British Columbia and similar settings (Piper and Normark, 2009).

CONSEQUENCES FOR VOLCANICLASTIC SEDIMENTATION MODELS

The existence of hyperpycnal flows feeding a volcaniclastic deep-sea fan introduces the idea of a gradual evolution of volcaniclastic sedimentation similar to the siliciclastic model. This model contrasts with the idea of catastrophic sedimentation related to flank collapses and pyroclastic flows. Following classifications made for turbidite systems by Richards et al. (1998) and Piper and Normark (2001), Cilaos is classified as a sand-rich system. Commonly, sand-rich systems are found in active tectonic settings, such as along the California margin or in the Gulf of Corinth (Piper and Normark, 2001). Space available for development of fans in these settings is reduced, so they tend to be thicker rather than wide (Richards et al., 1998; Piper and Normark, 2001). In these classifications, the Cilaos deep-sea fan represents an alternative model and shows a simple and predictable pattern, as (1) it formed in an open-ocean setting isolated from siliciclastic source, (2) it is a wide volcaniclastic sandy system similar to the siliciclastic ones, and (3) it shows lateral and vertical variations of facies and architecture.

This Quaternary model echoes the thick and well-developed volcaniclastic turbidite systems described in ancient geological series like in the Kalgoorlie Sequence in Australia (Krapez and Hand, 2008), or in the Lower Mesozoic Mineral King caldera complex in Sierra Nevada

(California; Busby-Spera, 1985). In those areas, sediments were essentially supplied by reworking of volcaniclastic deposits. Analogue structures to those described in this article are observed, such as channelized and unchannelized deposits, cross-bedded structures, or braided plain channels (Busby-Spera, 1985; Krapez and Hand, 2008).

Quaternary deep-sea volcaniclastic sediments are widespread in many basins with high economic interest (Fisher, 1984; Alibés et al., 1999; Elliott and Parson, 2008), and they represent a complexity for the mechanism of siliciclastic sedimentation. In those areas, volcaniclastic sedimentation is mainly seen as linked with episodic and ephemeral massive processes (Manville et al., 2009). Nevertheless the existence of the Cilaos turbidite system underlines the lack of understanding of Quaternary volcaniclastic sedimentation linked to long-term surface processes.

Flash floods, especially those that destroy bridges, are considered to be catastrophic events. Nevertheless, at the Quaternary scale and considering the phenomena of volcanic flank collapses, they are consistent events because they are linked with climate and long-term physical processes. Because the Cilaos fan is the result of flood supply of sediment by rivers, it appears to be a good example of evolution from a catastrophic sedimentary system model characteristic of volcanic environments to a gradual sedimentary system model characteristic of siliciclastic environments. It also provides a good opportunity to study in detail the different facies and architecture related to subaerial flood processes.

ACKNOWLEDGMENTS

We thank the captains and crews of the N/O *L'Atalante* and N/O *Beautemps-Beaupré* for their excellent work during cruises FOREVER and ERODER1, respectively. The technical and financial support of L'Institut Francais de Recherche pour l'Exploitation de la Mer, Service Hydrographique et Océanographique de la Marine, and Centre National de la Recherche Scientifique–Institut National des Sciences de l'Univers is also gratefully acknowledged. Thanks are due to Hervé Douris for the photos of la Rivière Saint-Étienne. An early draft of the manuscript was significantly improved based on comments from D.J.W. Piper, P.J. Talling, J.-L. Schneider, R.B. Wynn, and D.G. Masson. We are also grateful to the two anonymous reviewers for their constructive reviews. This is Institut de Physique du Globe de Paris (IPGP) contribution 3025.

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